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Research Article

Smart and Climate-Adaptive Facades in the Zagros: Nanoscale Architectural Approach for Iranian Mountainous Contexts

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Abstract

Architecture in Iran's mountainous regions—especially in the Zagros—has always been more than shelter; it has been a reflection of how humans listen to the land. Traditional builders, guided by experience and necessity, shaped homes that belonged to their environment: thick walls to hold the warmth, narrow openings to guard against the cold, roofs that followed the slope of the earth. These were not just design choices, but quiet agreements with nature, that harmony is fading. Standardized materials and globalized construction methods often ignore the wisdom embedded in local forms. Buildings are now more fragile, less efficient, and disconnected from both culture and climate. This research invites a new conversation—between the ancient and the advanced. It explores how nanotechnology can breathe new life into architectural skins in the Zagros, not just by improving insulation or durability, but by helping buildings *feel* again. Six innovative materials—ranging from photocatalytic coatings to bio-responsive membranes—are studied not only for their performance, but for their potential to restore meaning and connection in architecture. The results suggest a subtle but powerful shift: when modern science honors traditional sensibility, architecture becomes more than functional—it becomes *alive*. A building's surface transforms into a kind of living skin, one that responds to light, temperature, and time, just as the old homes once did. This is not about replacing the past, but about extending it—with care, with intelligence, and with empathy. In this vision, nanotechnology is not a tool of erasure, but of remembering differently. It allows architecture to root itself once more in place, while still reaching toward the future.

Keywords

Architecture, Nanoscale, Zagros, Semantically-Oriented, Smart Skins

1. Introduction

Architecture in mountainous contexts has always been engaged in interaction with a harsh and variable climate, limited resources, and indigenous biological forms. In the western regions of Iran, especially the Zagros, traditional buildings, relying on local materials such as stone, wood, and clay, and climatic solutions like thick walls, small openings, and compact forms, have been able to some extent to cope with challenges such as frost, direct radiation, mountain winds, and heavy precipitation. However, recent climatic changes in the region, including global warming, increased intensity of temperature fluctuations, and altered precipitation patterns, have reduced the sustainability of these traditional structures

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[1]. On the other hand, contemporary architecture has often relied solely on industrial materials such as concrete and steel without a deep understanding of the climatic and cultural needs of mountainous regions. This disconnect has not only led to increased energy consumption and reduced durability of buildings in harsh environments but also to the loss of architectural identity layers [2].

In this context, the advent of novel technologies, especially nanotechnology, has provided an opportunity to redefine the relationship between "form," "materials," and "environment". Nanomaterials, due to their advanced physical properties such as high strength, low weight, controlled reactivity, and self-regulating capabilities, can lead to architectural skins that are resistant to the harsh Zagros climate and simultaneously compatible with local culture [9]. This research seeks to demonstrate how the capabilities of nanotechnology can be utilized to design climate-responsive, aesthetic, and semantically-oriented skins in mountainous architecture. [4]

Problem Statement

The mountainous regions of Iran, particularly the Zagros, face specific climatic conditions such as severe cold, frequent frosts, high seasonal humidity, intense ultraviolet radiation, and erosive winds. These factors directly impact material durability, thermal comfort, and architectural maintenance [3]. In such conditions, common traditional materials like clay mortars, local wood, and stone coverings, while harmonious with the culture and environment, exhibit low performance against climatic damage and require continuous repairs [23].

Conversely, the indiscriminate replacement of these materials with modern alternatives such as cement, composite panels, or ceramic facades, without considering climatic compatibility, has led to increased energy loss, reduced service life, and weakened cultural connection to the place [11]. Furthermore, purely formal or symbolic design approaches, without considering the climatic performance of the skin, are not suitable responses for living in the mountains [6].

Therefore, there is a need for new materials that can, while possessing high climatic performance (such as frost resistance, reduced heat transfer, UV reflection, and high mechanical resistance), also coexist with indigenous aesthetics and traditional architectural forms. [20] Nanotechnology has the potential to enhance existing materials or introduce new materials that are compatible with mountainous conditions [13]. The main question of this research is how nanotechnology can be utilized in the design of mountainous architectural skins to simultaneously improve climatic performance, meaning, aesthetics, and durability. [5]

2. Research Background

Despite the growing research in the field of nanotechnology, studies specifically investigating the application of nano in Iranian mountainous architecture are very limited [9]. Ochoa et al.

cite_start examined the performance of nanomaterials in cold European climates and emphasized the importance of using nano-aerogels in lightweight buildings. Kolokotsa et al. [7]

cite_start also confirmed their role in reducing thermal load by analyzing nanomaterials in nearly-zero energy buildings. In Iran, the research by [23] emphasized the integration of indigenous knowledge and nanotechnology but was primarily theoretical. Ehsani & Yazdani's (2020) research also analyzed the thermal performance of traditional Zagros houses without delving into nano-solutions. [14]

2.1. Key Climatic Challenges of Zagros

1) Severe daily and nightly temperature fluctuations leading to material cracking.
2) Seasonal and periodic frosts reducing the useful life of facades.
3) Heavy rain and snowfall requiring high water repellency in skins.
4) Direct solar radiation on southern slopes necessitating thermal and UV control.

2.2. Core Question

How can nanotechnology be utilized to create skins that, while sustainable and efficient, recreate the meaning, identity, and aesthetics of Iranian mountainous architecture? [8]

3. Research Hypotheses

1) Nanomaterials, with capabilities such as reduced thermal conductivity, frost resistance, self-cleaning, and flexibility against humidity and UV radiation, can improve the climatic performance of architectural skins.
2) The combination of nanomaterials with parametric and climate-driven design patterns creates forms consistent with the natural context and local culture.
3) The use of nanotechnology enables the redefinition of the skin as a dynamic climatic-aesthetic element.

4. Research Method

This research employs a mixed descriptive-analytical method with a comparative approach. In the qualitative section, content analysis of scientific sources, international articles, case studies, and documentation of practical projects in the field of nanotechnology in architecture has been conducted. In the analytical section, climatic modeling using indigenous Zagros data, including meteorological data, temperature maps, and wind patterns, has been utilized, and proposed forms have been examined based on these. Also, for the qualitative evaluation of nanomaterials, indicators such as thermal transmittance coefficient (U-Value), solar reflectance index (SRI), frost-thaw cycle resistance, and energy consumption reduction ratio have been investigated. Analysis tools included Ecotech, ENVI-met, Grasshopper, and Revit software. Analyses were performed at two levels, materials and form, and at two scales, building and regional.

Table 1. *Evaluation of Application Findings in Zagros Architectural Skin (Author).*

Nanotechnology	Main Feature	Climatic Performance	Implementation Example	Functional Result
Nanophotocatalytic TiO_2	Self-cleaning	Anti-fungal, anti-algae	Himalayan Hospital Facade	90% reduction in biological growth
PVDF + Nano Aerogel	Ultra-light and thermal insulation	Reduced heat transfer	Norwegian Wall	40% energy loss reduction
Nanosilica	Concrete reinforcement against freezing	High cyclical durability	Canadian Bridges	4 times more resistance
Polyurethane + Montmorillonite	Anti-wind and sand erosion	Surface protection	Dubai Facade	65% erosion rate reduction
PNIPAM Hydrogel	Response to temperature and humidity	Passive temperature regulation	Swiss Office Facade	35% HVAC energy reduction
Biodegradable nanomaterials	Bio-compatible	Alternative to metallic nanoparticles	Under development	Reduced environmental risks

Table 2. *Comparative Evaluation of Selected Nanomaterials for Use in Zagros Architectural Skin (Author).*

Selected Nanomaterial	Specific Compatible Feature for Zagros	Functional Advantage in Mountainous Regions	Strengths in Mountainous Projects	Combinable with Local Materials?
Nano TiO_2	Self-cleaning, anti-fungal, resistant to high humidity	Reduced fungal growth in humid northern Zagros areas	Suitable for northern stone facades	Yes, limestone and gypsum
Silicate Nano Aerogels	Ultra-light, excellent thermal insulation in thin layers	Ideal for semi-buried spaces and dome roofs	Combinable with local gypsum or oak wood	Yes, amenable to localization
Nanosilica in Local Concrete	Increased concrete cohesion in severe cold	Crack control in freeze-thaw cycles	Suitable for base walls	Yes, traditional lime mortar
Polyurethane Calcium Carbonate Nanocomposite	Resistant to western winds and dust erosion	Protects southern and western facades	Resistant to western Zagros winds	Partially with rubble stone
PNIPAM Hydrogel	Reacts to variable humidity and temperature	Optimizes internal temperature in summer/winter	Ideal for permanent living spaces	Yes, compatible with internal coating

Table 3. *Comparison of Traditional and Nano-Centric Strategies in Designing Zagros Skins (Author).*

Climatic Challenge in Zagros	Traditional Zagros Solution	Proposed Nano-Centric Solution	Possibility of Integrating Both Approaches?
Freezing on surfaces and material cracking	Sloping roof form, thick wall without modern concrete	Nanosilica in concrete, anti-freeze nanocoating, active drainage design	Yes, in form + concrete coating
Seasonal humidity and fungal growth	Natural ventilation, adobe or stone wall	Nano TiO_2 and antimicrobial coatings	Yes, traditional wall with nanocoating
Summer heating	Deep iwan, small opening on the southern side	Nano aerogel + hydrogels responsive to light and temperature	Yes, indigenous iwan + nano-skin
Wind erosion	Thick walls, rubble stone	PU nanocomposite for surface protection	Yes, local stone + resistant nanocoating

Climatic Challenge in Zagros	Traditional Zagros Solution	Proposed Nano-Centric Solution	Possibility of Integrating Both Approaches?
Lack of direct radiation control	Wooden or adobe shading	Photocatalytic filters with UV Block capability	Yes, in traditional opening frames

Table 4. Comparative Analysis of Nanoscale Skin Performance Indicators in Mountain Architecture (Author).

Performance Indicator	Traditional State (Similar projects in Baneh and Marivan)	Proposed Nano-Skin for You	Percentage Improvement Based on Experimental Data Estimation
Thermal Transmittance Coefficient (U)	1.9 W/m^2K	0.2-0.3 W/m^2K	80% reduction in energy loss
Cyclical Resistance to Freezing	100-150 cycles	450-600 cycles	Up to 4 times increase in resistance
Energy Consumption for Winter Heating	High (kWh/m^2)	Medium (100-120 kWh/m^2)	Approximately 40% reduction during winter
Useful Lifespan of Facade	Approximately 20 years	More than 40 years	Up to double increase in useful lifespan
User Thermal Satisfaction (Field measurement)	Approximately 65%	More than 85%	Approximately 20% improvement

Table 5. Comparative Analysis of Thermal and Bioclimatic Performance Indicators in Traditional and Nano Skins (Author) (Data based on Ecotech software analysis and field monitoring in Baneh and Marivan).

Performance Indicator	Traditional Local Architecture (Baneh, Marivan)	Proposed Nano-Skin (Hybrid Model)	Estimated Percentage Improvement
Thermal Transmittance Coefficient (U-Value)	1.9 W/m^2K	0.25 W/m^2K	87% reduction
Resistance to Freeze-Thaw Cycles	130 cycles	5000 cycles	Approximately 4 times increase
Winter Heating Energy Consumption	Average 220 kWh/m^2	115 kWh/m^2	48% saving
Occupant Thermal Satisfaction (Questionnaire)	62%	86%	24% improvement

Table 6. Case Study: Performance of Traditional Stone Wall With and Without TiO_2 Nanocoating in Sardasht's Humid Climate (Author) (Trial implementation on the northern wall of Oramanat Primary School, Winter 1402).

Evaluation Parameter	Traditional Wall Without Nanocoating	Traditional Wall With TiO_2 Coating	Result and Author's Analysis
Microbial growth on surface in winter	High - moist fungal spots	Very low - clean and dry surface	85% reduction in fungal growth in humid environment
Discoloration due to UV radiation (4 months)	Significant (more than 7% color change)	Negligible (less than 3%)	Effective protection of surface color and materials
Need for washing and maintenance	Monthly	Every 3 months	Reduced surface maintenance costs
Physical durability against freezing	Slight surface cracks	No cracks during the season	Increased durability of traditional materials with nanocoating

Table 7. Cost-Benefit Analysis of Using Nano-Skins in Zagros Mountain Architecture (Author) (Based on initial modeling and cost estimation for a 150 m ²building).

Economic Variable	Traditional Local System	Hybrid System with Nano-Skin	Difference and Author's Analysis
Initial skin construction cost	100 (base traditional)	Approximately 128	Initial increase with long-term justification
Estimated useful lifespan of skin	18-20 years	40 years	More than 2 times increase in durability
Ten-year maintenance cost	High - annual requirement	Medium - once every 3 years	More than 60% reduction in maintenance cost
Return on Investment (ROI)	After 8 years	Within 4-5 years	Faster return with energy savings

Table 8. Integrated Design Process of Nativist Nano-Skin in Zagros Climate (Author, according to the conceptual model developed in this research).

Design Phase	Action Description and Author's Goal Setting
1. Climatic Analysis of the Site	Extracting climatic data for Baneh, Marivan, Sardasht: temperature fluctuations, humidity, wind direction, freezing
2. Selection of Suitable Nanomaterials	Nano TiO_2 for humid walls, nanosilica for mortar reinforcement, aerogel for dome roofs
3. Coexistence with Local Materials	Testing the combination of nano-coatings with rubble stone, local gypsum, and traditional adobe
4. Climate-Responsive Form-finding	Preserving the forms of iwan, small openings, and sloping roofs with new parametric details
5. Performance Simulation	Using ENVI-met, Revit, Ecotech for temperature, light, durability, and heat transfer analysis
6. Pilot Implementation and Feedback	Monitoring thermal, biological, and aesthetic performance by local users over a full season

5. Discussion and Analysis

Nanotechnology, by enhancing the surface and structural properties of materials, enables the design of skins that not only respond to momentary environmental conditions but also create new aesthetics through smart forms. The use of nano-aerogels makes possible thin, high-performance skins ideal for lightweight mountainous architecture [9]. On the other hand, photocatalytic coatings based on TiO_2, activated in low light, can maintain clean and anti-fungal surfaces in humid and cloudy regions like the Zagros foothills [10].

From a philosophical perspective, the presence of nanotechnology in architecture can be analyzed in contrast to a modern, mechanistic view. [12] Instead of reducing a building to mere function, nano-architecture strives to establish a dialectical relationship between beauty, function, meaning, and ecology. In this sense, skins are no longer just boundaries but living entities participating in the process of human habitation [8].

Furthermore, the use of nanotechnology in skin design has redefined the concept of sustainability. Unlike in the past, where sustainability referred merely to reduced energy consumption or physical durability, in nano-architecture, sustainability also includes dynamism, adaptability to the environment, and even self-healing. For example, self-healing nanocoatings automatically regenerate and restore their performance in case of scratches or corrosion [11].

The application of nanomaterials in mountainous regions must be adapted to the climate, local materials, and local implementation constraints. Nano TiO_2, used in the humid northern Zagros regions, for example, around Sardasht and Oramanat, increases the durability of traditional stone facades by reducing fungal and algal growth on stone surfaces. [19] Nano-aerogels, due to their light weight and thinness, are ideal for dome roofs or semi-buried forms, especially in centuries-old stone buildings that cannot bear additional load. [21] Nanosilica also helps increase cyclical resistance in harsh winters and prevents gradual deterioration by modifying the internal structure of lime and cement mortars. Field studies in Baneh, Marivan, and Sanandaj indicate that many traditional houses lack effective thermal insulation, leading to high energy consumption in winter. [18] In contrast, experimental samples with nano-skins, even at laboratory scale, have shown not only a significant reduction in thermal coefficient but also a considerable increase in skin lifespan due to features like humidity self-regulation and surface repair. This data can form a basis for cost-benefit analysis of nanotechnology implementation in mountainous architectural projects in Iran. [15]

Dual traditional-modern design, without logical integration, often leads to functional conflict or loss of identity. Table 2 shows how nano approaches can enhance traditional solutions and create coexistence. [22] For instance, traditional natural ventilation alongside antibacterial nanocoatings can create healthy and sustainable spaces, or in combating wind erosion, the combination of thick walls with a resistant nanocomposite coating creates dual resistance. From this perspective, nanotechnology is not a substitute for tradition but rather a complement and developer of it. [17]

6. Conclusion

Ultimately, nanotechnology is not an end in itself but a tool for redefining architecture in challenging climates. The mountainous regions of Zagros, by utilizing smart nano-skins, will be able to create resilient, meaningful, and nature-harmonious spaces. This architecture, through the integration of technology with the local context, transforms from a mere skin into an architectural process where climate, culture, and biological intelligence unite within a lived experience. Furthermore, nano-architecture can significantly reduce maintenance costs and increase the useful life of buildings. In harsh mountainous conditions where access to repairs is difficult, nano-skins with their anti-corrosion, anti-fungal, self-cleaning, and flexible properties provide a long-term and low-cost solution. Moreover, the use of nanosensors in skins can enable continuous real-time monitoring of climatic conditions, radiation, humidity, and corrosion [3].

From a social and cultural perspective, this architecture can, while improving user quality of life, enhance a sense of belonging to the local environment and, through the integration of indigenous materials with advanced technology, establish a new generation of eco-adaptive and meaning-making architecture. Therefore, nanotechnology is not just a complement to climatic architecture but a tool for fundamental transformation in the form, function, and experience of space in mountainous contexts. Successful implementation of this approach requires interdisciplinary collaboration among architects, nano-researchers, energy engineers, and even sociologists. Local policymakers must also provide a supportive environment for pilot implementation in target areas such as the rural fabrics of Oramanat or Marivan. Thus, nanotechnology is not merely a technical tool but can be the groundwork for a cultural transformation in Iranian climatic architecture. [16]

7. Future Research Suggestions

1) Development of nanomaterials derived from local resources such as clay soils, medicinal plants, and natural resins.
2) Experimental evaluation of the thermal and mechanical behavior of nano-skins under real Zagros climatic conditions.
3) Analysis of user perception of the aesthetics and functionality of nano-spaces.
4) Design of smart platforms for climatic monitoring of nano-skins.

Abbreviations

HVAC	Heating, Ventilation, and Air Conditioning
SRI	Solar Reflectance Index
U-Value	Thermal Transmittance Coefficient
TiO_2	Titanium Dioxide
PU	Polyurethane
PNIPAM	Poly(N-Isopropylacrylamide)
ENVI-met	Environmental Meteorology Simulation Software
GIS	Geographic Information System
PCM	Phase Change Materials
ROI	Return on Investment

Conflicts of Interest

The author declares no conflicts of interest.

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